Soil Mechanics and Geology
23CVB102

Semester 2 2024 | In-Person Exam Paper

This examination is to take place in-person at a central University venue under exam conditions. The standard length of time for this paper is **3 hours**.

You will not be able to leave the exam hall for the first 30 or final 15 minutes of your exam. Your invigilator will collect your exam paper when you have finished.

Help during the exam

Invigilators are not able to answer queries about the content of your exam paper. Instead, please make a note of your query in your answer script to be considered during the marking process.

If you feel unwell, please raise your hand so that an invigilator can assist you.

You may use a calculator for this exam. It must comply with the University's Calculator Policy for In-Person exams, in particular that it must not be able to transmit or receive information (e.g. mobile devices and smart watches are **not** allowed).

Answer **ALL EIGHT** questions from **Section A** and **TWO** questions from **Section B**. **Section A** is worth 40 marks and **Section B** is worth 60 marks.

A 5-page Formulae Sheet is provided.

Continues/…

…/continued

SECTION A
(Answer all EIGHT questions)

Students are advised to spend approximately 70 minutes on Section A

A1. A sample of soil passing the 63-micron sieve was tested to determine its consistency (Atterberg) limits. The results are as follows:

Table QA1.1 Liquid Limit test data

Cone Penetration (mm)	14.8	17.5	19	22.4	24.7
Moisture Content (w%)	57.8	60	61.2	63.7	65.7

Table QA1.2 Plastic Limit test data

Test Number	1	2
Moisture Content (w%)	26.6	27.3

Using the information in **Table QA1.1** and **Table QA1.2**, determine the Liquid Limit, Plastic Limit, Plasticity Index, and soil classification.

[5 marks]

A2. A 6 m-thick layer of saturated CLAY (γ_{sat} = 21 kN/m^3) is underlain by SANDSTONE. The groundwater level is at ground level (i.e. at the top of the CLAY layer). A surcharge of 50 kPa is rapidly applied to the surface of the CLAY. Calculate the total stress, effective stress, and pore-water pressure immediately following application of the surcharge at a depth of 6 m (i.e. at the bottom of the CLAY layer).

[5 marks]

A3. The normal total stress acting on a plane within a soil is 205 kPa and the effective shear strength parameters are:

Peak: c_p' = 6 kPa, ϕ_p' = 28°. Residual: c_r' = 0 kPa, ϕ_r' = 11°.

When the pore-water pressure is 65 kPa, determine the maximum shear strength that can be obtained on the plane, and the shear strength after considerable shear strain.

[5 marks]

A4. A field pumping test was performed in a 12 m-thick layer of SAND, which was underlain by CLAY. The initial water level was at a depth of 2 m in the SAND. Two observation wells were sunk 16 m and 34 m away from the pumping well. At a steady state pumping rate of 0.01 m^3/s, the drawdown in the observation wells was 1.95 m and 0.97 m, respectively. Determine the coefficient of permeability of the SAND.

[5 marks]

Section A continues/…

A5. For compaction of a cohesive soil, draw and label a diagram of the typical relationship between dry density and water content, including approximate locations for the 0%, 5% and 10% air voids lines.

[5 marks]

A6. In an oedometer test, a specimen of saturated clay reduced in thickness from 28.20 mm to 13.30 mm, reaching 50% consolidation in 20 minutes. How long would it take a 5 m thick layer of this saturated clay to reach the same degree of consolidation?

[5 marks]

A7. Explain in brief the basic principle of the 'Standard Penetration Test' (SPT), which is carried out *in situ* during borehole drilling in soils. For which ground conditions would you consider the SPT more suitable than attempting undisturbed (tube) sampling?

[5 marks]

A8. Describe and illustrate which two processes occur to enable movement along non-planar discontinuities.

[5 marks]

SECTION B
(Answer TWO questions, each question is worth 30 marks)

Students are advised to spend approximately 110 minutes on Section B

B1. a) Consolidated-Undrained (CU) triaxial tests were performed on three specimens of the same saturated CLAY. The results at failure are given in **Table QB1.**

Table QB1. Triaxial test data

Cell pressure (kPa)	140	200	280
Deviator stress at failure (kPa)	172	225	291
Pore pressure at failure (kPa)	26	33	47

i) Using the data in **Table QB1**, construct a table that shows values of major and minor principal stresses at failure in both total stress and effective stress terms. Show in full how you have calculated all answers.

[6 marks]

ii) Determine the effective stress shear strength parameters for the CLAY by plotting three effective stress Mohr circles.

[8 marks]

Question B1 continues/…

b) Describe the shear stress versus shear strain response of a stiff, overconsolidated CLAY, referring to '*dilation*', and '*peak*', '*critical state*', and '*residual*' shear strengths. Use appropriate illustrations to support your answer.

[8 marks]

c) A long CLAY slope exists at an angle of 10°. The water table is parallel to the ground surface and lies at 0.75 m below ground level. The CLAY bulk unit weight (above and below the water table) is 21.5 kN/m^3, effective cohesion is 0 kPa, and effective friction angle is 30°.

i) Calculate the slope's factor of safety against shear failure along a 5 m-deep potential shear surface, which is parallel to the ground surface.

[4 marks]

ii) The long CLAY slope subsequently fails along a 1.5 m-deep shear surface. Determine the residual friction angle on this shear surface.

[4 marks]

B2. A site underlain by SAND is to be developed as part of a construction project (**Figure QB2**). Development of the site includes a retaining wall and a double row of sheet piles to support a temporary excavation 3 m deep and 5 m wide. Beneath the SAND is stiff CLAY. Properties of the SAND are:

$$c' = 0 \text{ kPa}, \ \phi' = 33°, \ \gamma_{dry} = 18 \text{ kN/m}^3, \ \gamma_{sat} = 20 \text{ kN/m}^3, \ k = 3\times10^{-5} \text{ m/s}$$

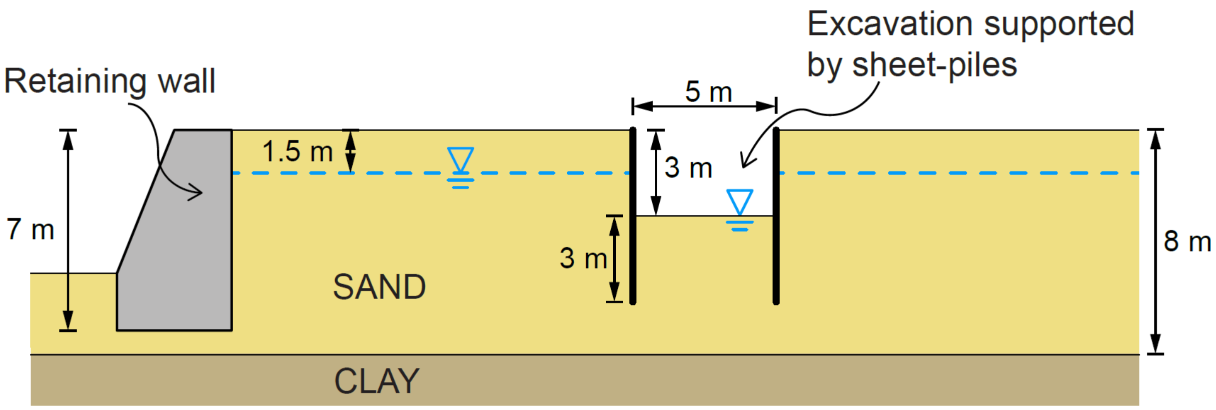


Figure QB2. Cross-section of the site comprising SAND

a) The 7 m high retaining wall shown in **Figure QB2** supports SAND with an effective friction angle of 33°. The groundwater level is 1.5 m below ground level. Determine the total forces acting on the back of the wall (active thrust) per metre run. Assume hydrostatic pore-water pressures behind the wall.

[10 marks]

Question B2 continues/…

b) Draw a flow net for groundwater flow into the pumped excavation supported by the sheet piles. Assume that the groundwater level is at 1.5 m below ground level outside of the excavation, the groundwater level inside the sheet piles is at the base of the excavation, and flow through the underlying CLAY layer is negligible (i.e., treat it as impermeable for the purpose of drawing the flow net). [*Note: You must draw **Figure QB2** to scale to obtain a solution. Ignore the adjacent 7 m high retaining wall for the purpose of drawing the excavation flow net.*]

[10 marks]

c) Using your flow net from part B2(b), calculate the pore-water pressure acting at the base of the sheet piles (i.e. at a depth of 6 m below the top of the sheet piles).

[6 marks]

d) Using your flow net from part B2(b), calculate the flow of water per day (m^3/day) per metre run into the excavation.

[4 marks]

B3. a) A 10 m high embankment (γ = 25 kN/m^3) is to be constructed on a 5 m thick layer of SAND that is overlying a 4 m thick layer of CLAY, which is underlain by free-draining SAND. The CLAY stratum has m_v = 0.60 m^2/MN and C_v = 0.8 m^2/year. Constructing the embankment took 1 year.

i) Calculate the ultimate primary consolidation settlement.

[2 marks]

ii) Draw both instantaneous and corrected primary consolidation settlement versus time curves, as a result of primary consolidation of the CLAY layer, for the 2 years after the start of construction, taking into account the construction time. Use curve (1) on the T_v versus U_z chart in the formula sheet and average degree of settlement increments U_z of 0.1 in your calculations.

[15 marks]

iii) Briefly explain how the consolidation time and final primary consolidation settlement in (i) and (ii) would be affected if the base layer underlying the CLAY was impervious non-draining rock instead of free-draining sand.

[3 marks]

b) At a vertical stress of 200kPa, the void ratio of a saturated soil sample tested in an oedometer is 1.52 and lies on the normal consolidation line. An increment of vertical stress of 150 kPa compresses the sample to a void ratio of 1.43.

i) Determine the compression index Cc of the soil.

[3 marks]

Question B3 continues/…

…/Question B3 continued

ii) The sample was unloaded to a vertical stress of 200 kPa and the void ratio increased to 1.45. Sketch a graph of void ratio versus log of applied pressure for this sample. What is the overconsolidation ratio of the soil at this stage?

[4 marks]

iii) If the soil were reloaded to a vertical stress of 500 kPa, what void ratio would be attained? Show this reloading step on the graph drawn in part (ii).

[3 marks]

B4. In an old limestone quarry, a 50 m long, 25 m high rock slope shows signs of instability. There are a couple of bench levels visible, but these are narrow (width <2 m) and partially obscured by scree and lush vegetation. Approximately mid-slope a prominent fault surface can be observed. This fault has resulted in a 2 m relative displacement of the bedding planes. The fault appears to be younger than the formation of the joint sets A and B.

The survey of the rock slope resulted in the stereographic plot of **Figure QB4**. Partial results of the survey are shown in **Table QB4**.

Table QB4 Summary of survey results.

Feature	Dip and strike	Spacing
Rock face		-
Joint set A		3 m
Joint set B		1 m
Bedding plane		0.5-2.5 m
Fault		3.2 m

Friction angle	

a) Using the stereographic plot (**Figure QB4**), complete the missing dip and strike and friction angle information in **Table QB4**. Include your answer in your answer book.

[6 marks]

b) Identify the mode(s) of rock slope failure that are apparent from the stereographic plot. Provide details on which discontinuities are relevant, the dip/strike of potential plunge lines, and give an assessment of the likely dimensions of these potential rock slope failures.

[12 marks]

c) Considering the information provided, what range of rock slope failure mitigation interventions would be appropriate?

[6 marks]

Question B4 continues/…

d) The Norwegian 'Q' system uses three ratios to express the quality of a rock mass. Briefly explain what these three ratios represent.

$$Q = \frac{RQD}{Jn} + \frac{Jr}{Ja} + \frac{Jw}{SRF}$$

[6 marks]

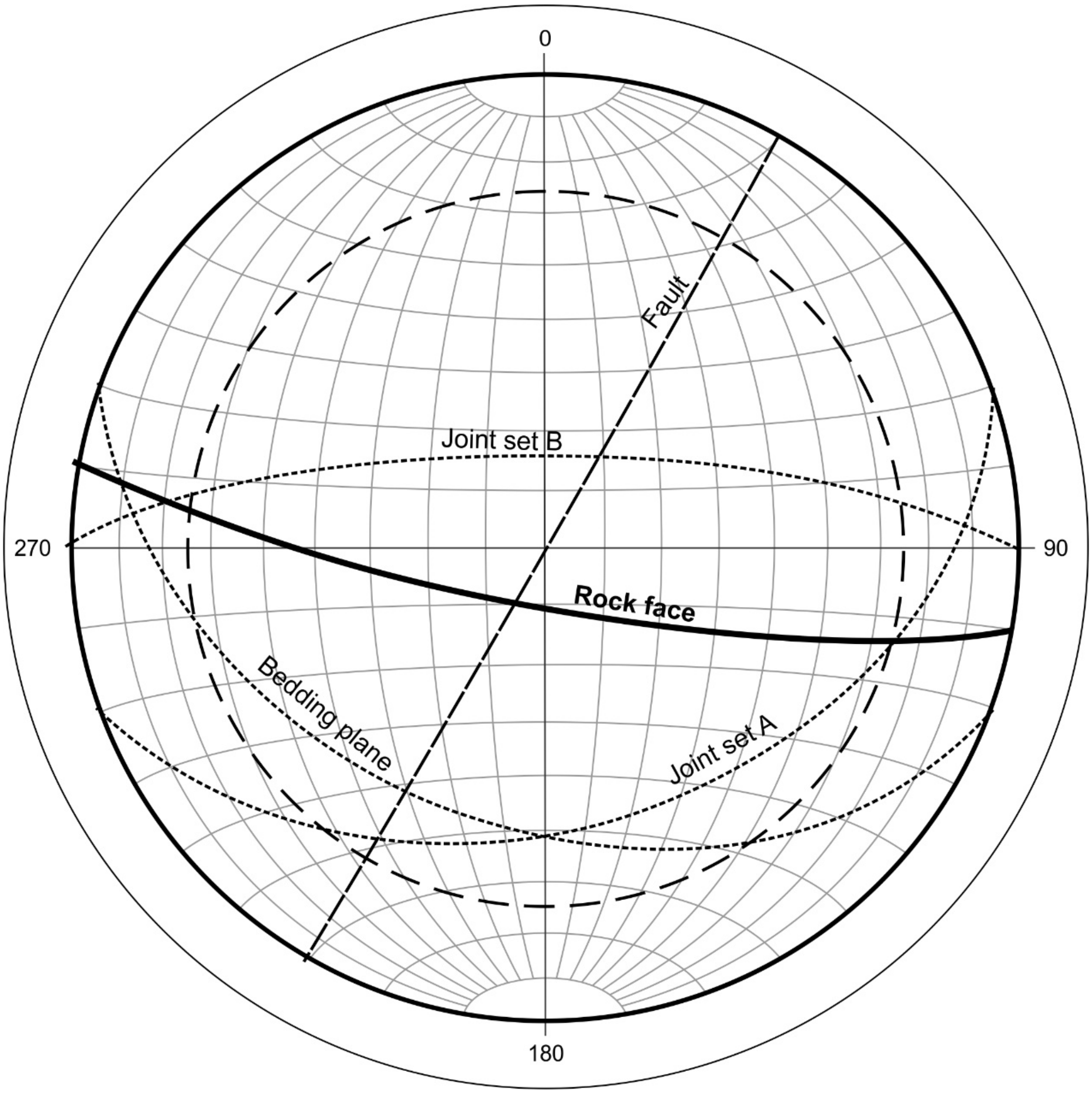


Figure QB4. A stereographic plot representing the rock face and its discontinuities.

A Smith, A El-Hamalawi, P Fleming, T Dijkstra

Continues/…

…/continued

LOUGHBOROUGH UNIVERSITY
School of Architecture, Building and Civil Engineering
Soil Mechanics & Geology (CVB102) - FORMULAE SHEET and CHARTS

Classification

Specific gravity	G_s	=	density of solids/density of water = ρ_s/ρ_w
			$= \gamma_s/\gamma_w$
Bulk density	ρ	=	overall mass of soil per unit volume = m/V
Bulk unit weight	γ	=	overall weight of soil per unit volume = W/V
Unit weight of water	γ_w	=	ρ_w g = 9.81 kN/m^3
Submerged (buoyant) density	ρ'	=	$\rho - \rho_w$
Dry density (mass of solid particles per unit volume of soil)			
	ρ_d	=	$\rho/(1 + w)$
Density of water	ρ_w	=	1000 kg/m^3 = 1.0 g/cm^3
Moisture content	w	=	mass of water in soil/mass of solids = m_w/m_s
Total soil volume	V	=	$V_s + V_v = V_w + V_s + V_a$
Air content	A_v	=	volume of air/volume of soil = V_a/V
Degree of saturation	S_r	=	V_w/V_v = volume of water/volume of voids
Void ratio	e	=	V_v/V_s = volume of voids/volume of solids
Porosity	n	=	$V_v/V = V_v/(V_s + V_v) = e/(1 + e)$
Plasticity Index	PI	=	LL - PL
Grading, Coefficient of Uniformity	C_u	=	D_{60}/D_{10}
Grading, Coefficient of Curvature	C_c	=	$\dfrac{(D_{30})^2}{D_{10}\,D_{60}}$

Phase relationships

Moisture content	w	=	$S_r \cdot e / G_s$	These are examples - you can derive any
Bulk density	ρ	=	$\rho_w G_s(1 + w)/(1 + e)$	phase relationship required from the
Unit weight	γ	=	$\gamma_w G_s(1 + w)/(1 + e)$	definitions above.

Seepage

Darcy's Law	v	=	k.i , q = A.k.i
Bernoulli's Theorem	H	=	$z + u/\gamma_w = z + h_w$
Hazen's approximation	k	~	$0.01\, d_{10}^2$ (k in m/s, d in mm)

k from laboratory falling head tests $k = \dfrac{2.3aL}{A(t_2 - t_1)} \log\left(\dfrac{h_1}{h_2}\right)$

k from well pumping tests (unconfined flow) $$k = \frac{2.3q\log(r_2/r_1)}{\pi(h_2^2 - h_1^2)}$$

k from well pumping tests (confined flow) $$k = \frac{2.3q\log(r_2/r_1)}{2\pi H(h_2 - h_1)}$$

Stratified soils $k_h = \frac{\Sigma kH}{\Sigma H}$

$k_v = \frac{\Sigma H}{\Sigma(H/k)}$

Piping $i_c = \frac{\gamma'}{\gamma_w}$

Flow nets $q = k\,(\frac{Nf}{Nd})\,H$

Anisotropic soil scale factor for x = $\sqrt{\frac{k_v}{k_h}}$ k' = $\sqrt{k_v k_h}$

Boundary condition $\frac{k_1}{k_2} = \frac{\tan\alpha_1}{\tan\alpha_2}$

Modification to position of exit phreatic surface in an embankment dam:

β	30°	60°	90°
Δa/a	0.36	0.3	0.26

Shear strength

Coulomb $\tau_f = c + \sigma \tan \phi$

$\tau_f = c' + \sigma' \tan \phi'$

Mohr's Circle $\sigma_1 - \sigma_3 = P/A$ (= deviator stress)

$\tau_{max} = (\sigma_1 - \sigma_3)/2$ (undrained)

$\theta = 45 + \varphi/2$

Pore Pressure parameters

$\Delta u = B\Delta\sigma_3 + A.B\,\Delta(\sigma_1 - \sigma_3)$

$A.B = \bar{A}$

$\bar{A}_f = u_f/(\sigma_1 - \sigma_3)_f$ (f refers to failure)

Consolidation and Compression

Coefficient of volume compressibility $$m_v = -\frac{\Delta\varepsilon_v}{\Delta\sigma'} = \frac{\Delta e}{(1+e_0)(\Delta\sigma')} = \frac{e_0 - e_1}{(1+e_0)(\sigma_1' - \sigma_0')} = \frac{a_v}{(1+e_0)}$$

Coefficient of compressibility $$a_v = \frac{e_0 - e_1}{\Delta\sigma'}$$

Volumetric strain $$\Delta\varepsilon_v = \frac{\Delta H}{H_0} = -\frac{\Delta e}{1+e_0}$$

$$\Delta e = e_0 - e_1$$

Voids ratio e = water content * specific gravity = w. G_s (saturated)

Compression $\Delta H = s_{max} = H_0 m_V \Delta\sigma'$

$$\frac{\Delta H}{H_0} = \frac{e_0 - e_1}{(1+e_0)} = \frac{c_c \log\left(\frac{\sigma_1'}{\sigma_0'}\right)}{(1+e_0)}$$

where e_0 = initial voids ratio, e_1=final voids ratio

σ_0' = initial effective stress, σ_1' = final effective stress

ΔH = primary consolidation settlement, H_0 = initial thickness

$\Delta\sigma'$= difference in effective stress

Compression Index $C_C = (e_0 - e_1) / \log(\sigma_1' / \sigma_0')$

Coefficient of Consolidation $c_V = \dfrac{k}{m_V . \gamma w}$

Overconsolidation Ratio $R = \sigma'_{max} / \sigma'_{current}$

Degree of consolidation $U_z = \dfrac{e_0 - e}{e_0 - e_1} = \dfrac{\sigma' - \sigma_0'}{\sigma_1' - \sigma_0'} = 1 - \dfrac{u^e}{u^0} = \dfrac{s_t}{s_{max}}$

Time factor $T_V = \dfrac{c_V t}{d^2}$

$U_Z = 0.9$ for $T_V = 0.848$; $U_Z = 0.5$ for $T_V = 0.196$ Note: c_V in m^2/year

Finite difference calculation of excess pore pressure and settlement:

$$\bar{u}_{i,j+1} = \bar{u}_{i,j} + \frac{c_v \Delta t}{(\Delta z)^2}(\bar{u}_{i-1,j} + \bar{u}_{i+1,j} - 2\bar{u}_{i,j})$$

$$S_t = \sum_0^t m_v \Delta z \Delta\bar{u}$$

Correction for construction period:

For $0 \le t < t_C$: $s_t^{corrected} = s_{t/2}^{instant} (\Delta\sigma^t / \Delta\sigma^{net}) = s_{t/2}^{instant} (t/t_c)$

For $t = t_C$: $s_t^{corrected} = s_{tc/2}^{instant}$

For $t > t_C$: $s_t^{corrected} = s_{t-tc/2}^{instant}$

Compaction of Earthworks

Dry Density $\rho_d = \rho_b / (1+w)$ $\rho_d = (G_S / (1+e)) . \rho_w$

ρ_b = Bulk Density

ρ_d = Dry density

$\rho_d = (1-A) / ((1/\rho_s) + (w/\rho_w))$

Note: w = moisture content

Lateral Earth Pressure and Retaining Walls

$K_0 = 1 - \sin\phi'$

$K_a = (1 - \sin\phi') / (1 + \sin\phi')$

$K_p = (1 + \sin\phi') / (1 - \sin\phi')$

$P_a = K_a.\sigma'_z – 2.c'\sqrt{K_a}$

$P_p = K_p.\sigma'_z + 2.c'\sqrt{K_p}$

Bearing Capacity

$Q_{ult} = c.N_c.S_c + p_0.N_q.S_q + ½.\gamma'.B.N_\gamma.S_\gamma$

Bearing capacity factors:

$N_q = e^{(\pi \tan\phi')} \tan^2\left(45° + \frac{\phi'}{2}\right)$

$N_c = \frac{N_q - 1}{\tan\phi'}$

$N_\gamma = 2(N_q - 1)\tan\phi'$

ϕ'	N_q	N_c	N_γ
0	1	5.14	0
5	1.6	6.9	0.1
10	2.5	8.5	0.5
15	3.9	10.8	1.6
20	6.4	14.8	3.9
25	10.7	20.8	9.0
30	18.4	30.1	20.1
35	33.3	46.1	45.2
40	64.2	75.3	106.1
45	134.9	133.9	267.8
50	319.1	266.9	758.2

Shape factors:

Shape	S_c	S_q	S_γ
Strip	1.0	1.0	1.0
Rectangle	$1 + \frac{B}{L}\frac{N_q}{N_c}$	$1 + \frac{B}{L}\tan\phi$	$1 - 0.4\frac{B}{L}$
Square, circle	$1 + \frac{N_q}{N_c}$	$1 + \tan\phi$	0.6

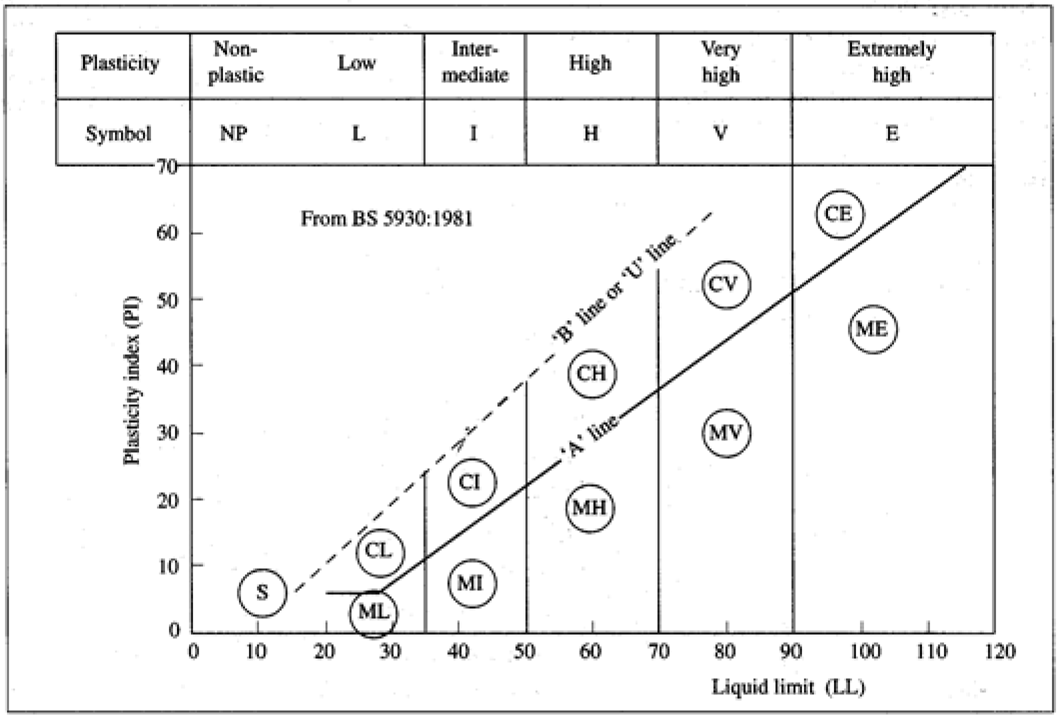
Slope Stability

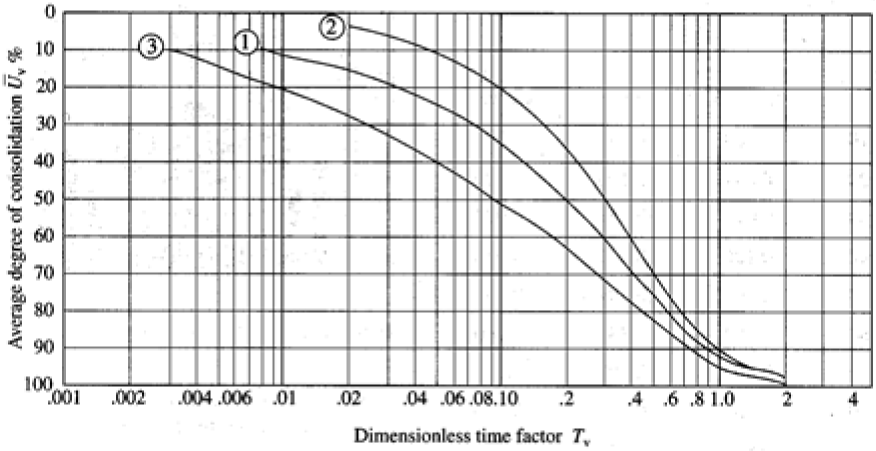
Translational slides:

$$\mathrm{FoS} = \frac{\tau_{\max}}{\tau} = \frac{c' + (\gamma z - \gamma_w m z)\cos^2\beta \tan\varphi'}{\gamma z \sin\beta \cos\beta}$$

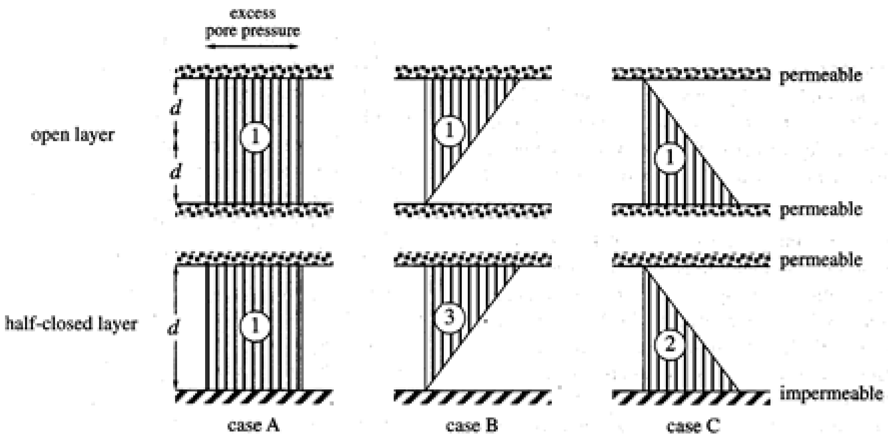
Circular slides:

$$\mathrm{FoS} = \frac{c_u r^2 \theta}{Wd}$$





a) $\overline{U}_v$ - T_v relationships



b) Variations of initial excess pore water pressure